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Total-System Performance Assessment for the Yucca Mountain Site

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ABSTRACT

Yucca Mountain, Nevada, is under consideration as a potential site for a repository for high-level radioactive waste. Total-system performance-assessment simulations are performed to evaluate the safety of the site. Features, events, and processes have been systematically evaluated to determine which ones are significant to the safety assessment. Computer models of the disposal system have been developed within a probabilistic framework, including both engineered and natural components. Selected results are presented for three different total-system simulations, and the behavior of the disposal system is discussed. The results show that risk is dominated by igneous activity at early times, because the robust waste-package design prevents significant nominal (non-disruptive) releases for tens of thousands of years or longer. The uncertainty in the nominal performance is dominated by uncertainties related to waste-package corrosion at early times and by uncertainties in the natural system, most significantly infiltration, at late times.

INTRODUCTION

The U.S. Department of Energy (DOE) is studying Yucca Mountain, Nevada, as a potential site for disposal of high-level radioactive waste. The site has been the subject of an extensive site-characterization effort, and a series of total-system performance assessments (TSPAs) has been conducted over the past decade, with increasing complexity and detail in the models used for the assessments. The general approach for conducting a TSPA is to (1) identify and screen potentially relevant features, events, and processes to develop scenarios, (2) develop models, (3) estimate parameter ranges and uncertainties, (4) perform calculations, and (5) interpret results. Some of these steps can be carried out in parallel, and the procedure generally must be repeated iteratively as knowledge is gained. The TSPA model for Yucca Mountain includes numerous submodels for natural systems, engineered systems, and the interactions between them. Disruptive events are also modeled (primarily igneous activity, but with consideration of other possible disruptive events as well). As implied by step (3), a probabilistic approach is used, in which uncertainties are propagated through the system so that the effects of uncertainties on the final results can be analyzed.

Two major TSPA studies have been completed recently. They are documented in *Total System Performance Assessment for the Site Recommendation* (TSPA-SR) [1] and *Supplemental Science and Performance Analyses* (SSPA) [2]. This paper provides a brief summary of those studies.

Regulatory context is important for TSPA since one of the purposes of TSPA is to determine whether the site complies with the relevant regulatory standards. Regulations governing potential waste disposal at Yucca Mountain have been promulgated by the U.S. Environmental Protection Agency (EPA) [3] and the U.S. Nuclear Regulatory Commission (NRC) [4]. Of particular note is that the regulations specify a performance period of 10,000 years and a dose

limit of 15 mrem/yr (0.15 mSv/yr) to the reasonably maximally exposed individual due to releases from the undisturbed Yucca Mountain disposal system.

FEATURES, EVENTS, AND PROCESSES

A defensible TSPA must consider all relevant features, events, and processes (FEPs) that could significantly affect the evaluation of repository performance. A systematic process for radioactive-waste disposal has been developed and applied over the past 20 years [5,6]. The process utilizes the following steps:

1. Identify FEPs that are potentially relevant to the long-term performance of the disposal system.
2. Classify the FEPs to support evaluation of completeness and to facilitate screening.
3. Screen the FEPs to identify those that should be included in the TSPA analysis and those that can be excluded from the analysis.
4. Construct scenario classes (sets of related scenarios) from the retained (included) FEPs.
5. Screen the scenario classes to identify any scenario classes that can be excluded from the TSPA analysis.

The development of a comprehensive list of FEPs potentially relevant to the postclosure performance of the potential Yucca Mountain repository is an ongoing, iterative process based on site-specific information, design, and regulations. The Yucca Mountain Project (YMP) FEP list was initially developed from a comprehensive list of FEPs from other international radioactive-waste-disposal programs and was supplemented with additional YMP-specific FEPs from Project literature, technical workshops, and reviews. The YMP FEP list is open and may continue to expand if additional FEPs are identified during the site-recommendation and license-application processes. The YMP FEP list contained 1,797 entries as of December 2000, though there is considerable redundancy in the list because of its origins in lists from several international programs. A subset of 323 FEPs were identified as "primary" FEPs, which are general enough that the others ("secondary" FEPs) are encompassed by them.

Screening of primary FEPs (and scenario classes) is conducted using three criteria:

- **Probability.** FEPs that have less than one chance in 10,000 of occurring over 10,000 years may be excluded (screened out) from the TSPA on the basis of low probability.
- **Consequence.** FEPs whose exclusion would not significantly change the expected annual dose may be excluded (screened out) from the TSPA on the basis of low consequence.
- **Regulation.** FEPs that are inconsistent with regulatory guidance may be excluded (screened out) from the TSPA analysis. The most notable examples are the regulatory specification of the biosphere characteristics and human-intrusion scenario (e.g., [3], §197.21 and §197.26).

The results of the FEP screening are summarized in Appendix B, Section B.5, of [1]. Many FEPs are listed as partially included and partially excluded, which means that some aspects of the FEP are included in the TSPA, but some other aspects are screened out. An example is the FEP called "Climate change, global." It is included in the TSPA models for unsaturated and saturated groundwater flow, but effects on the biosphere are excluded because of the way the biosphere is prescribed in U.S. regulations.

Each of the retained primary FEPs was identified as either an expected FEP or a disruptive FEP. Expected FEPs are assumed, for the purposes of the TSPA, to have a probability of occurrence equal to 1 (i.e., the FEP is certain to occur—though the consequences may be

uncertain). Disruptive FEPs have a probability of occurrence less than 1 (but greater than the low-probability screening threshold noted above). The "nominal" scenario class was constructed to include all expected FEPs. A disruptive-performance scenario class includes disruptive FEPs in addition to all expected FEPs.

The retained disruptive FEPs were all associated with igneous activity or human intrusion. As specified by regulation, human intrusion is evaluated in a separate TSPA analysis. Therefore, the other disruptive-performance scenario class contains only FEPs related to igneous activity and is referred to as the igneous-disruption scenario class. The igneous-disruption scenario class is further subdivided into two scenarios: volcanic eruption (direct release) and igneous intrusion (indirect release via groundwater).

FEPs related to seismic damage to spent-fuel cladding were included in the nominal scenario class, rather than as a disruptive scenario. Other FEPs related to seismic events (ground motion and fault displacement) were screened out on the basis of low consequence. FEPs related to nuclear criticality were also screened out, on the basis of low probability.

The probability of occurrence for the igneous-disruption scenario class was derived from an expert elicitation of the annual frequency of igneous activity in the Yucca Mountain region. The inferred rate of activity indicates that the probability of recurrence at Yucca Mountain is small during the next 10,000 years, but it is greater than the one chance in 10,000 over 10,000 years that is specified in the regulations as the threshold above which a FEP must be included in the TSPA. The probability of the nominal scenario class is one minus the probability of the igneous-disruption scenario class. The probability of the nominal scenario class is therefore just slightly less than one. Note that human intrusion is considered separately and only in terms of consequence. The probability of human intrusion is not estimated or taken into account in the probabilities of the other scenario classes.

No further screening is possible at the scenario level. In summary, then, the TSPA consists of two separate analyses, the primary one consisting of two scenario classes, nominal and igneous disruption, and the other consisting of a stylized human-intrusion scenario class.

YUCCA MOUNTAIN DISPOSAL SYSTEM

This section gives brief descriptions of the Yucca Mountain site and the models that have been developed for it. More-detailed descriptions, but still at a relatively high level, can be found in Chapter 3 of the TSPA-SR report [1]. Full documentation is given in a series of process-model reports (PMRs) and analysis/model reports (AMRs). Because there are so many of them, citations will not be given here. The PMRs and AMRs (as well as the TSPA-SR report and other YMP reports) are available from the YMP (see <http://www.ymp.gov/doclist.htm>).

Natural setting

Yucca Mountain is located on federal land in southern Nevada approximately 160 km northwest of Las Vegas. The mountain is an irregularly shaped volcanic upland varying in elevation at its crest from 1,500 m to 1,930 m above mean sea level and characterized by approximately 650 m of relief. Yucca Mountain is located in the Basin and Range province of the western United States, within the region known as the Great Basin. Yucca Mountain is composed of volcanic rocks (tuffs) formed by eruptions of ash or magma from volcanic vents to the north from approximately 14 to 11.5 million years ago. There are alternating layers of welded and nonwelded tuffs. The terms welded and nonwelded refer to the degree of

consolidation of the rock when it was formed from volcanic ash millions of years ago. Welded tuff is hard, dense rock but is typically very fractured. Nonwelded tuff is softer and typically less fractured.

Present-day climate in southern Nevada is semiarid, with hot summers and mild winters. Average annual precipitation at Yucca Mountain is about 170 mm. The amount that infiltrates into the ground below the root zone is uncertain, but is thought to be between 0.4 and 12 mm/yr on average. Based on paleoclimate data, the climate has been wetter most of the time in the past, and by inference will be wetter most of the time in the future. Groundwater flow in the unsaturated zone (UZ) is primarily vertically downward. The most important exception is above a low-permeability zone below the potential repository location, where there is perched water. It is thought that lateral flow of up to hundreds of meters may exist within this perched zone.

The groundwater flow in the saturated zone (SZ) is generally to the southeast near the potential repository, with a transition toward the south and southwest farther south. Groundwater that has flowed beneath Yucca Mountain is probably captured at pumping wells 20 km or more to the south in the Amargosa Valley under present conditions. Under predevelopment conditions (before pumping began in the Amargosa Valley) during the current climatic state, natural discharge of groundwater from beneath Yucca Mountain probably occurred further south at Franklin Lake Playa, although spring discharge in Death Valley is a possibility. Under past, wetter, climatic conditions, groundwater discharge probably occurred at locations nearer to Yucca Mountain within the Amargosa Valley. The water table is typically 100 to 300 m below the ground surface near Yucca Mountain, although in the Amargosa Valley the water table can be at the ground surface as spring discharge.

Groundwater flow in the SZ below and directly downgradient of the potential repository at Yucca Mountain occurs in fractured, porous volcanic rocks at relatively shallow depths beneath the water table and in fractured carbonate rocks of Paleozoic age at much greater depths. At distances greater than about 10 to 20 km downgradient from the potential repository, where the volcanic rocks thin and are overlain by alluvium, groundwater flows either through the alluvium or the deep Paleozoic carbonates.

The nearest community in the direction of groundwater flow from the potential repository site is Amargosa Valley. The closest inhabitants to Yucca Mountain are at a location known as Lathrop Wells within Amargosa Valley, approximately 20 km south of the potential repository. There are approximately eight inhabitants at this location. Based on proposed NRC and EPA regulations, this area is the general site of a hypothetical farming community that was defined to be the critical group for purposes of the TSPA calculations. The dose receptor (the person who incurs a radiation dose) was taken to be the "average member of the critical group," which is essentially the same as the "reasonably maximally exposed individual." When the regulations were finalized recently [3,4], a closer location (approximately 18 km south of the potential repository) was specified. This change is expected to have only a small effect on the computed results that are discussed below.

Repository design and waste inventory

The potential repository location is within the Topopah Spring unit, in densely welded, highly fractured tuff. The potential repository would be in the unsaturated zone, roughly 300 m below the ground surface and another 300 m above the water table.

The design concept for the engineered barrier system (EBS) is for waste to be emplaced in 5.5-m-diameter drifts in large waste packages composed of a 2-cm corrosion-resistant (Alloy-22)

outer layer with a 5-cm stainless-steel inner layer, which provides structural strength and some radiation shielding. The waste packages would be emplaced on corrosion-resistant (Alloy-22) pallets on an invert composed of a steel structure and granular ballast fill (e.g., crushed welded tuff) at the base of the drift. There is to be a corrosion-resistant (titanium alloy) drip shield over the waste packages, which serves to reduce the effects of rock fall and dripping on the waste package. The base-case design does not include backfill in the emplacement drifts. However, flexibility is to be retained in the design so that backfill could be added before closure if desired.

Heat is an important consideration for the design. Because aging of the waste on the surface is not planned, the waste may be relatively hot when emplaced. Current intent is to maintain flexibility in the thermal-loading strategy until concerns about the acceptable temperature range have been resolved. The base case considered in the TSPA-SR [1] assumed an areal mass loading of approximately 60 metric tons of uranium (MTU) per acre, achieved by emplacing the waste packages in a "line load" configuration, with a spacing between waste packages of approximately 10 cm and a spacing between drifts of 81 m (center to center). Forced ventilation during a 50-yr preclosure period was assumed. The ventilation would remove a large portion of the heat and reduce the peak temperatures. Even lower peak temperatures can be achieved by increasing the duration of the preclosure ventilation period. A ventilation period of 300 years was considered in the SSPA [2], in order to investigate how potential repository performance might be affected by lower temperatures. (The lower-temperature case included other changes in addition to the longer ventilation period, including greater spacing between waste packages.)

The capacity of the potential repository is 70,000 MTU, consisting of 63,000 MTU of commercial spent nuclear fuel (CSNF), 4,700 MTU of vitrified high-level waste (HLW), and 2,300 MTU of DOE-owned spent nuclear fuel (DSNF). The waste-package reference design can hold 21 assemblies from a pressurized-water reactor (PWR). Roughly the same-size waste package can accommodate 44 assemblies from a boiling-water reactor (BWR), five HLW glass "logs" surrounding a central canister of DSNF, or a canister of naval spent nuclear fuel. Smaller waste packages, for 12 PWR assemblies or 24 BWR assemblies, are used for high-heat-producing or high-criticality-potential assemblies. As modeled in the TSPA, there would be 7,860 CSNF waste packages and 3,910 codisposal waste packages (packages containing HLW and DSNF) placed in the potential geologic repository.

Radionuclides contained in the waste packages include fission products from reactor operations, actinides from neutron capture in uranium and plutonium, and activation products from neutron irradiation of structural materials and trace elements. Altogether, these fission products, actinides, and activation products constitute well over 100 radionuclides that may be present in the waste packages at the time of the potential repository closure. A total of 26 radionuclides was considered sufficient to include in TSPA calculations, though only a subset of those are included in any given simulation, depending on the time period (e.g., 10,000 years or 1,000,000 years) and scenario class (e.g., nominal or igneous-disruption) being simulated.

Models

There is insufficient space here to describe the TSPA model in any detail. The discussion will be limited to a simple listing of the important subcomponents and an indication of whether they are implemented within the TSPA model itself or are external to it (see Table I). The external subcomponents are included in the TSPA model by means of tables of values (or process-model output files) developed prior to running the TSPA model. The software used for the TSPA model is GoldSim [7], which acts as an integrating shell that links all the various

subcomponent models. Some submodels are implemented using GoldSim's built-in functions, but the more complex ones are implemented by linking a separate program as a dynamically linked library (DLL).

Table I. TSPA subcomponents and implementation methods.

TSPA Subcomponent	Implementation Method
Climate and infiltration	External
UZ flow	External
Seepage into drifts	External/internal (DLL)
UZ transport	Internal (DLL)
SZ flow	External
SZ transport	External/internal (DLL)
Biosphere	External
Thermal hydrology and coupled processes	External
Chemical environments (in-drift & in-package)	External/internal
Radionuclide inventory	External
Drift degradation	External
Waste-package and drip-shield degradation	Internal (DLL)
Waste-form degradation	Internal
EBS flow and transport	Internal
Volcanic eruption	Internal (DLL)
Igneous intrusion	Internal
Human intrusion	Internal

TREATMENT OF UNCERTAINTY

Because it is not possible to have perfect knowledge or understanding of all the components of the disposal system, and because of the long time scales of interest, estimates of repository performance can never be certain. Thus, in considering the safety of a potential disposal site for high-level waste, it is important to take into account the effect of uncertainties on the conclusions.

The primary tool being used for uncertainty analysis of potential Yucca Mountain performance is the Monte Carlo method. The uncertainties of key model input parameters are quantified by assigning probability distributions to them. The total-system model is then run for multiple realizations of the system. Each realization represents a possible future history of the disposal system and has a unique set of values for the uncertain parameters, sampled from their distributions. Monte Carlo simulations are computed separately for the nominal, igneous-disruption, and human-intrusion scenario classes. Results for the nominal and disruptive scenario classes can be combined (with appropriate probability weighting) to obtain the overall mean annual dose, which is the quantity to be compared with U.S. regulatory standards. Similarly, the mean annual dose for the human-intrusion scenario class is also used for comparison to the standards. In order to emphasize the effects of the disruptive events, simulations with disruptive events are computed with nominal waste-package-degradation processes disabled. That way, the calculated radionuclide releases and doses are all directly caused by the disruptive event. The disruptive scenario classes, as defined previously, should

include all the nominal processes, so the annual dose for the disruptive scenario class would actually be an appropriate combination of doses from the disruptive simulation and the nominal simulation.

While the mean of the dose distributions is the key quantity specified by regulation, the entire distribution is of interest, because the distribution represents a quantification of the uncertainty in projected dose. Realizations that produce high dose estimates are of particular interest, and can be examined to determine the particular combinations of input values that lead to high calculated doses. In addition, results for each simulation can be examined in detail, including analysis of correlations of input parameters with the computed annual dose at various times, in order to determine which parameters and models have the greatest influence on the results.

CALCULATIONS

The TSPA model (GoldSim) can be run in a single-realization mode, which is sometimes done in order to conduct an in-depth examination of a particular realization. However, the model is normally run in a multiple-realization probabilistic mode so that effects of uncertainty can be analyzed. It has been found that 300 realizations are sufficient to provide numerical stability of the mean-dose results for nominal simulations, but 5000 realizations are needed to achieve reasonable stability for igneous-disruption simulations. The greater number of realizations is needed for disruptive simulations in order to achieve sufficient sampling density for the time of occurrence of the igneous-intrusion event. Because the time of human intrusion is fixed in a given simulation, 300 realizations are sufficient for human-intrusion simulations.

Since each realization of a multiple-realization simulation is independent from the others, GoldSim can run on a network, with multiple realizations computed simultaneously on as many processors as are available. This feature greatly facilitates probabilistic simulation of the complex TSPA model, in which a single realization can take hours to complete.

Three primary sets of TSPA simulations are described in the recent reports, along with many sensitivity analyses. The three are as follows:

- The base-case TSPA-SR model, which is described in the TSPA-SR report [1].
- The supplemental TSPA model, higher-temperature operating mode (HTOM), which is described in the SSPA report [2].
- The supplemental TSPA model, lower-temperature operating mode (LTOM), which is described in the SSPA report [2].

The first two cases (base case and HTOM) simulated essentially the same potential repository design, but with a number of differences in the component models. The third case (LTOM) used the same component models as HTOM, but simulated a lower-temperature design (lower thermal loading and longer preclosure ventilation period). Both nominal and igneous-disruption simulations were performed for each of these cases. Human intrusion was simulated only for the base-case TSPA-SR model.

Two goals of the SSPA work were to improve the quantification of some of the model and parameter uncertainties and to analyze in greater detail the effects of temperature on repository performance. Thus, many model changes from TSPA-SR to HTOM/LTOM are intended to improve the treatment of uncertainty or the treatment of temperature-dependence of various processes. In addition, some changes were results of new information (e.g., new data or new modeling) developed since completion of the TSPA-SR.

RESULTS

The results of the recent TSPA simulations are documented in Chapters 4 and 5 of [1] and Chapters 3 and 4 of [2]. A small subset of the available results is presented here. Selected nominal and igneous-disruption results are presented, but human-intrusion results are not discussed.

Nominal

Figure 1 shows a comparison of the nominal mean-dose results for the three cases discussed above: the TSPA-SR base case, the supplemental TSPA model higher-temperature operating mode, and the supplemental model lower-temperature operating mode. The HTOM and LTOM results are quite similar, even though there is a considerable difference in temperature between the two at early times (peak HTOM waste-package temperature is on the order of 160°C, whereas peak LTOM waste-package temperature is on the order of 80°C). This result indicates only a weak temperature-dependence in the calculated dose. On the other hand, there is a big difference between the base-case results and the supplemental-model results. The most important model changes causing this difference are the following.

- **Waste-package corrosion.** There are several significant changes in the waste-package corrosion model from the base case to the supplemental model. The change that had the largest effect was the addition of temperature-dependence to the model for waste-package general-corrosion rate. In the supplemental model, as temperature declines over time the general-corrosion rate gets very low, and the result is that most waste packages take significantly longer to fail. Waste-package failure drives the dose results to a great degree, as is clear from a comparison of the two plots in Figure 1. The importance of waste-package failure to the dose estimate will be discussed further below.
- **Premature waste-package failures.** The supplemental TSPA model includes a higher estimate of the probability that waste packages might fail prematurely because of improper heat treatment of the welds. The premature failures lead to a low mean annual dose before 10,000 years, whereas the base case has no waste-package failures, and therefore no dose, before 10,000 years.
- **Climate.** The base-case TSPA model used a simplified climate model with no climate changes except in the first 2,000 years. The addition of a more realistic climate sequence to the supplemental TSPA model causes many spikes in its dose curves after about 30,000 years, while the base-case mean dose curve is smooth.
- **Radionuclide mobilization and transport.** There are several changes from the base-case model to the supplemental model related to radionuclide mobilization and transport, including changes in the distribution of seepage that enters emplacement drifts, reductions in solubility for some key radionuclides (most importantly, ^{237}Np), and inclusion of some transport effects that had previously been neglected (a model for diffusive transport on thin films inside waste packages, sorption of radionuclides in the waste packages and in the drifts, and release of radionuclides that diffuse out of the EBS into the matrix continuum rather than the fracture continuum for UZ transport).

Figure 1. Mean annual dose (left) and mean fraction of waste packages failed (right) vs. time for the nominal simulations.

Source: [2], Figures 4.1-1 and 4.2.5-2a

The dose curves in Figure 1 are just the means of the distributions of dose at each time. The entire dose distribution can be examined to determine how much uncertainty there is in the dose calculations. Two examples are given in Figure 2: the distribution of doses at 10,000 years and the distribution of peak-dose values. The 10,000-year dose is of interest because the regulatory period is specified as 10,000 years. Peak dose is of interest because it represents the maximum risk from the potential repository. The regulations also specify that an evaluation of peak dose is to be included in the Environmental Impact Statement. Note that the dose in many realizations of the supplemental TSPA model is still increasing at 1,000,000 years, so that the peak is actually not yet attained. It is evident from both Figures 1 and 2 that the peak doses are much lower in the supplemental model than in the base-case model. This is partially due to the lower rate of waste-package failures and partially due to other model changes, such as the reduction in estimated solubility for some radionuclides.

Figure 2. Histograms of dose at 10,000 years (left) and peak dose within 1,000,000 years (right) for the nominal simulations.

Source: [2], Figures 4.1-9 and 4.1-11

It is useful to know which radionuclides are the greatest contributors to the calculated dose. At early times (the first 60,000 to 90,000 years) the dose is dominated by the highly soluble, very mobile radionuclides, ^{14}C , ^{99}Tc , and ^{129}I . After that, the dose is dominated by ^{237}Np , with

increasing contributions by several other actinides at late times (^{231}Pa , ^{226}Ra , ^{227}Ac , ^{242}Pu , ^{229}Th , ^{230}Th , ^{210}Pb).

Igneous disruption

Figure 3 shows a comparison of igneous-disruption mean-dose results for the base case, HTOM, and LTOM. There are two distinct periods: At early times (for approximately 2000 years in the base-case model, and for nearly 20,000 years in the supplemental model) the dose is dominated by the effects of volcanic eruption through the potential repository. At later times, the dose is dominated by groundwater transport from waste packages damaged by igneous intrusion. Once again, the HTOM and LTOM results are quite similar to each other and rather different from the base-case results. In particular, the mean annual dose due to volcanic eruption is higher in the supplemental model, but the mean annual dose due to igneous intrusion is lower in the supplemental model. The most important model differences are the following.

- **Biosphere.** The dose from an eruptive event is increased by a factor of about 2.5 in the supplemental model because of an increase in the estimate for the particulate concentration in air.
- **Volcanism.** Several parameters used in describing volcanic events are different in the supplemental model as compared to the base-case model, including higher probability of an eruption within the potential repository, higher number of eruptive conduits for an eruption, and higher wind speed.
- **Radionuclide mobilization and transport.** The decrease in dose due to igneous intrusion in the supplemental TSPA model is a result of the changes in the nominal models for radionuclide mobilization and transport that were mentioned previously. Additional structure in the mean-dose curves caused by the additional climate changes in the supplemental model is also evident. Note that release and transport of radionuclides in groundwater for an igneous-intrusion event are modeled using the same models that are used for the nominal simulations.

Figure 3. Mean annual dose vs. time for the igneous-disruption simulations.

Source: [2], Figure 4.3-1

The important radionuclides are different for the eruptive and intrusive cases, both because of the difference in transport pathways and because of the different time scales. The eruptive dose is dominated by high-inventory, low-half-life radionuclides: ^{241}Am , ^{238}Pu , ^{240}Pu , ^{239}Pu , and ^{90}Sr . The intrusive dose is dominated by ^{239}Pu and ^{237}Np .

Sensitivity/importance analysis

Several types of uncertainty and sensitivity analysis have been performed for the TSPA results ([1], Chapter 5; [2], Chapter 3). One example is discussed here: stepwise rank regression analysis on the dose results for a nominal simulation.

Regression analysis is a tool for quantifying the strength of input-output relationships in a simulation. To this end, a stepwise linear rank-regression model is fitted between total dose at a given time (or some other performance measure) and all sampled input variables. Parameters are ranked on the basis of how their exclusion would degrade the explanatory power of the regression model. The importance-ranking metric used for this purpose is the uncertainty importance factor, which is defined as the loss in explanatory power (reduction in R^2 when the parameter is removed from the regression model) divided by the coefficient of determination of the regression model (R^2). Note that the uncertainty importance factor quantifies what proportion of the total spread (variance) in total dose explained by the regression model can be attributed to the variable of interest.

Results of stepwise rank-regression analysis for the nominal simulation using the TSPA-SR base-case model are shown in Figure 4. Note that the earliest time analyzed is 40,000 years because before that time there are too many realizations with zero dose, which causes regression results to have poor statistical significance. The regression results show that waste-package corrosion parameters have the greatest impact on dose for the first 150,000 years or so, but that infiltration has the greatest impact after that. To say it another way, uncertainty in waste-package performance causes the greatest uncertainty in dose at early times, but uncertainty in infiltration (and other natural-system parameters) causes the greatest uncertainty in dose at late times. The lack of waste-package importance at late times occurs because most waste packages have failed already in the base-case model by about 200,000 years, and so there is no longer much uncertainty associated with waste-package failure in the model. Analogous results

Figure 4. Results of uncertainty importance analysis for the nominal simulation with the TSPA-SR base case.

Source: [1], Figures 5.1-4 and 5.1-11

SCC = stress corrosion cracking

for the supplemental TSPA model would be expected to have a longer period of importance of the waste package because the waste packages fail over a longer period in that model (see the right-hand plot in Figure 1).

CONCLUSIONS

A systematic TSPA process has been carried out for the potential repository site at Yucca Mountain. Features, events, and processes that could be important to performance have been identified, categorized, and screened. Computer models for the important subsystems have been developed and linked into a viable total-system model. Uncertainties in the submodels and parameters have been studied and quantified. Numerous simulations of the total system have been carried out, including many that were conducted for purposes of sensitivity analysis. The results have been analyzed and presented in Project reports. Results to date show that risk is dominated by igneous activity at early times because the robust waste-package design prevents significant nominal (non-disruptive) releases for tens of thousands of years or longer. The peak dose in the model occurs hundreds of thousands of years in the future, and is dominated by nominal processes, including waste-package corrosion, infiltration and seepage of water, and radionuclide transport. If the site is found to be suitable and officially recommended, further TSPA analyses will be conducted to support the license application.

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